RIACS

COLLABORATION TECHNOLOGY AND SPACE SCIENCE

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Much of space science now involves cooperation between multiple organizations and people. Scientific activities are multi-disciplinary and require access to distributed resources. Design of new aircraft and space platforms involves teams of contractors and NASA personnel spread across the country and beyond. Operations of both manned and unmanned platforms require teamwork among on-board personnel, mission control, and technical specialists. In all of these cases, coordination and collaboration among the players are key to the success of the mission and activity.

At the same time, a significant body of technical capability is emerging in the computer science research community and the commercial computer and communications industry. The combination of advances in computing and communications has made possible automated support of team activity through a wide variety of tools ranging from simple electronic mail and electronic access to data bases through to networking for advanced planning and scheduling and scientist-to-scientist and engineer-to-engineer interaction.

In this paper, we summarize available collaboration technologies and their potential applications to space science. We then describe the investigations into remote coaching paradigms and the role of a specific collaboration tool for distributed task coordination in supporting such teleoperations.

Introduction and Summary

Remote interaction is becoming a necessity in many areas of science. Interaction with remote instrumentation will be necessary because instruments are inaccessible (such as the space telescope) or operate in an environment hostile to people (such as unmanned deep ocean vehicles). Remote interaction with colleagues will be necessary whenever the appropriate mix of talents to address an interdisciplinary problem is not collocated anywhere. Remote interaction with information will be necessary when the data are too vast to be replicated or managed at a single location (such as the global seismic database). Some of the most pressing scientific challenges facing us, such as that of global change, are inherently distributed and exhibit all of these properties: remote interaction with instruments, colleagues, and data is essential to solving them.

The technology to support these remote interaction is advancing rapidly. A very high-speed national network will support research and education as an initial foundation for a national information infrastructure.[1] Supercomputers and high-speed workstations are becoming ubiquitous. Open systems standards are making these facilities interoperable and more accessible to the research community. Integrating these technologies into the infrastructure to support scientific research could significantly improve pace and quality of such research. Large scientific projects can be carried out productively over long durations and distances as long as all elements of the infrastructure are carefully integrated. New collaborations will arise because distance will no longer constrain carrying out tasks or sharing data. Data streams produced by sensors and instruments around the world will be aggregated and the new findings distributed across the research community.

Fortunately, there are a variety of tools already available, both from the research community and the commercial sector. The required research into system architecture can therefore begin by addressing the appropriate system to take advantage of existing tools. It should focus on the interfaces between such tools, the enhancements and modifications required to make those tools fully accessible and usable by the scientific community, and the degree to which the tools work together to support scientific research. Examples of available tools include electronic mail, electronic file transfer, shared files, remote database access, multimedia mail, on-screen video, support for structured interactions, and simulated instruments.[2]

RIACS, in collaboration with NASA Ames Research Center, is investigating the application of such collaboration tools to a concept denoted as "remote coaching." Imagine an experiment onboard Space Station Freedom being conducted by onboard flight crew. The Principal Investigator (PI) for the experiment, who is located on the ground, is presumably more expert in the experiment (particularly in dealing with off-nominal events) than the onboard personnel, if for no other reason than the onboard crew must deal with a large variety of experiments. In addition, the relatively long mission durations planned will lead to inevitable skill loss over time. Involving the PI in real-time in the conduct of an experiment therefore has great potential for assisting the onboard crew in carrying out the experiment

and dealing with off-nominal and serendipitous events. This concept is referred to as remote coaching.[3] We have been investigating the applicability and effectiveness of different communication media and tools in supporting remote coaching.

One particular investigation has been into a distributed check-list, a computer-based tool that enables a group of people (such as the onboard crew, ground based investigator, and mission control) to synchronize their actions while following a pre-defined task sequence.[4] We initially assume that the people involved only have computer workstations available to them for communication. Hence, our approach it to study how the computer can be used to help a group remain synchronized while at the same time provide full flexibility of the flight crew to set the pace and remain on their own operational schedule. This autonomy has been shown to contribute to productivity and morale.

In this paper, we summarize available collaboration technologies and their potential applications to space science. We then describe the investigations into remote coaching and the role of the distributed check list tool in supporting such teleoperations.

Collaboration Support Tools

There are a large number of space science activities that involve teams of researchers working in collaboration. In this section, we discuss technologies that can be used to support these teams and therefore increase their effectiveness. We divide the technologies into those which are relatively mature (so the major effort involves integration into the overall system) and those where research is required.

Initial Capabilities

Networking research over the past three decades has resulted in the development and demonstration of a wide variety of tools to support collaborative activities. However, many of these tools have not progressed beyond laboratory demonstrations. Providing these tools to the user communities discussed above will require a concerted effort at integration and enhancement to assure that they satisfy the user requirements.

Electronic Mail. Fundamental to team efforts is the ability to communicate rapidly and reliably. Electronic mail provides this function in a way unequalled by other forms of communications. While electronic mail technologies need enhancements in the areas of interoperability (there are too many incompatible systems), graphics capability, privacy, and user support (such as white pages services), this technology has been available and proven over the last two decades.

Electronic File Transfer. As teams undertake cooperative development and analysis activities, they need to share results. Many of these results are represented as computer files. The technology to accomplish file transfer is well proven.

Shared Files. While the technology to exchange files is well proven, the ability to share information through such files is still quite crude. The only common information representation widely accepted today is ASCII text representation (and even there, such facilities as tab settings sometimes give problems.) Standard file representations for higher level functionality (such as graphics and research data representations) are available and are being used in limited communities, but need to be more widely standardized and adopted.

Database Access. Related to the ability to share files is the ability to store and retrieve data from shared databases. Again, as in shared files, the technology and standards to accomplish this has been demonstrated in the research community and in limited user communities, but further work is needed to insure widespread standardization and adoption.

Access Control and Authentication. It is critical that, as teams share information and provide for shared control of resources, appropriate security mechanisms be provided. Crude forms of such technologies have been demonstrated and could be adopted while further research is conducted in this area.

Multimedia Mail. While electronic mail in its current form (text) provides highly useful functionality, team activities require integration of other media, such as graphics, sound, spread sheets, and scanned images. We already have seen the demonstration of the utility of such media through the widespread use of fax. Multimedia mail is available already through a number of proprietary products and limited demonstrations of interoperability have been accomplished. However, widespread adoption of multimedia mail will require the emergence of a powerful mechanism for interoperability.

Multimedia Conferencing. Video conferencing has already been shown to be helpful in supporting team activities. Providing computer support to such conferencing, allowing groups to use computer tools in the course of the conference, will enhance such group work. Incorporating video and audio in every workstation (a trend we see already in new commercial workstations) will facilitate such teaming. Prototype demonstrations have been conducted, but further work is required to achieve a widely adoptable system.

Structured Interaction Support. In recent years, several tools have been developed that are aimed at supporting the process of collaboration and teamwork. While some are available commercially, these tools have generally been developed in a proprietary architecture, targeted at specific machines and operating systems. Widespread use in the communities above will require porting these systems to an open architecture.

Future Technologies

Advances in the underlying computer and communications technologies have made possible new tools to support collaboration. These will tend to emerge from the computer science community as a result of ongoing research combined with the recognition of potential applications. We provide some examples of possible future tools.

Hypermedia Conversation Support. We saw above that multimedia electronic mail and conferencing along with support for structured interactions has already been demonstrated. Coupled with hypermedia tools (such as Hypercard and Hyperties), there is a possibility of providing support for team interactions. A hypermedia database can be created and maintained that tracks the team interactions and provides an ongoing record of the interactions. This would provide a long-term record of design decisions, operational problems and corrections, and research approaches.

Computer-based User Agents. New ideas in distributed systems coupled with high bandwidth networks makes possible the increased use of distributed processes acting on behalf of the user. An example of such an agent is the "Knowbot" described by Cerf and Kahn in their work on a digital library.[2] Such a Knowbot would conduct a search of the distributed library to find the desired information. The use of intelligent user agents would greatly increase the utility of the overall information system.

Interoperable Data Description. As science becomes more multi-disciplinary, there is an increasing need for access to data derived from different sensors and other sources. For users to be able to take advantage of such data, the data must be described in a manner that is understandable to the analysis system. Yet, it may not be possible to use a common data format across disciplines. Research is required into methodologies for describing data in an interoperable manner that recognizes the unique requirements of the individual data. For example, research into global environmental change will require the understanding of data from atmospheric, space, ocean, and ground sensors as well as outputs of computer models.

The Challenge

As we saw above, there are a variety of space science activities that involve teams and can take advantage of computer based support for such collaborations. There are also a number of tools and technologies both available and emerging that can support such collaborations. The challenge is to make such technologies accessible to the user communities and, particularly in for upcoming programs and missions, to ensure that there is an adequate robustness of understanding and experience in the user communities to utilize these technologies effectively and efficiently when they are needed.

Historically, many new technologies have been left dangling at the end of the research cycle waiting to be adopted by some user community or integrated into commercial products. Since the potential users have had little experience with such technologies, they have little basis for asking for those tools.

One approach that has proved to be successful is the user-oriented rapid-prototyping testbed..[5] The concept is a partnership between users and developers to integrate a prototype information system tailored to the user's environment. The users then conduct their activities using these prototype tools. As a result, the users understand better their requirements and the potential technologies to solve their problems, and the developers better understand the desirable directions that future technology enhancements and upgrades.

In the case of collaboration technology for space science and missions, it is clear that there are a large number of potential tools and applications. No single user can afford to pull together the entire system, nor can the technology developers afford to integrate a system without a strong user involvement. However, through teamwork among the various users and developers, a set of prototype systems tailored to different user environments can be integrated and tested. By taking advantage of initiatives of other agencies, particularly the NSF Collaboratory Initiative, a kernel system consisting of a number of basic tools can be assembled. Such a system could then be used as the basis for systems more tailored to the user applications.

Remote Coaching

Remote coaching refers to an application of collaboration technology to an aspect of teleoperations where people are shown remotely how to carry out precise experimental procedures by means of audio-visual and computer-based means. As mentioned above, future space crews must maintain high skill levels in a wide variety of technical areas despite the fact that they will be physically separated from normal training and skill maintenance facilities. It is possible that they will need refresher courses periodically in their chosen specialties as well as coaching and education in totally new ones.

While this area of telescience holds great potential for carrying out future manned and unmanned space activities safely and efficiently, it is necessary to be able to show that the many promises which telescience offers are actually achieved. A rapid-prototype experiment will be described briefly that quantified some of the operational features involved in a remote coaching application.

The Ames' Remote Coaching Facility (RCF) was used to carry out an experiment involving eight volunteers (mean age = 34 years) who had to carry out several complex plant physiology procedures under the remote guidance of a principal investigator (PI).[3] . These procedures included plant specimen selection and dissections, instrument selection, operation of fixative hardware (e.g., a cryo-freezer unit mockup), and special sample storage equipment, labelling and stowage procedures, and operation of the telecommunications equipment. After about four hours of individual training, each "Mission Specialist" was

tested over two separate two hour-long periods. The intent was to find out how effectively they would use three available telecommunications links to carry out high quality science as rated by two independent judges. The three nodes were connected by a medium resolution color TV system, an audio communications system, and linked Macintosh computers with carefully designed checklists for the complex science procedures that had to be carried out remotely.

There were three operational telescience nodes in this study. The first was a bio-isolation chamber (known as a "glove box") mockup similar to one planned for Space Station Freedom's Laboratory Module. Inside this chamber were three miniature color TV cameras, a high resolution color monitor, and a Macintosh computer (with mouse) in addition to other experimental hardware. The Mission Specialist stood in front of the glove box with his or her hands inserted into special armlets and gloves inside the sealed chamber. The second operations node was the PI's working station. He had two 19" color TV monitors, two miniature color TV cameras (one of which could be moved by him at will), a Macintosh computer, and duplicate experimental hardware as was found in the glove box. The third and final test node was the Payload Operations Control Center (POCC) where there were two large format color TV monitors, a Macintosh computer, a video channel switching unit, intercom controls, and other equipment. The mission controller monitored quality of science, ensured that mission timeliness were being followed, monitored operations to ensure safety, switched TV camera views to all parties, and otherwise acted as an overall coordinator.

The experiment was designed so that predictive parametric data would be obtained. In this way the results could have wider applicability than otherwise. The video channel was failed unexpectedly during later data runs for three of the test subjects. When it failed it did so completely so that not even the PI or Mission Controller had video. This failure occurred when the video was critical in learning how to carry out the required scientific procedure. The objective was to find out whether relatively untrained subjects would find new ways to work around the failure and what impact the failure would have on quality of science. In short, most did work around the failure. Nevertheless, the PI remarked, "The loss of video resulted in many errors committed by the crew that were not caught by the ground PI. Most of these errors would have resulted in the loss of the tissue sample, and some would have resulted in a safety hazard and/or injury to the crew." Several subjects requested that the PI use a computer graphic outline of a specimen leaf in conjunction with his mouse to move a cursor to indicate what and where to perform the required sample selection and cutting.

The audio channel also was failed unexpectedly for another two subjects at a point just before they had to request authorization from the ground to take a specific action. Both subjects simply waited, expecting the "problem" to be solved by someone else. We think that because the video was less obtrusive than the audio, when the audio failed the subjects did not rely upon the video as much or as rapidly as they relied on the audio when the video failed. The audio channel turned out to be the most important communications channel of all.

The computer-based procedural checklist channel was also failed for another subject at a time when there was little likelihood that she could have memorized the required steps at the point of failure. The descriptive text on the screen was scrambled so as to be unreadable. The subject was an experienced biologist; the failure was little more than an

inconvenience for her. She merely asked the PI to read the illegible steps. In general, the audio-visual channels were relied upon for task accomplishment more than was the linked computer workstations. Of course this finding will be influenced significantly by the types of tasks that must be carried out remotely.

For two other subjects an unexpected collaboration failure occurred where the Mission Controller simply did not respond verbally to the subject for a three minute-long period at a point when he was supposed to authorize the subject to activate a robot sequence. Both parties were supposed to back one another up monitoring the robot's motions. One of these subjects waited the full three minutes while the other went ahead and activated it without authorization.

This study provided useful lessons concerning how these three telescience support technologies (i.e., video, audio, linked workstations) are used to support remote coaching of complex life sciences procedures. Several of these lessons included: (1) The capability to conduct rapid prototyping studies was shown to be a cost- and time-effective way to validate new telescience hardware and procedures, to obtain empirical data, and to gain valuable hardware- and software-specific insights, (2) Properly designed audio-visual telescience support hardware (generally) will produce higher quality science output on Space Station Freedom. Whether or not computer-based workstations with procedural checklists may contribute significantly to productivity, error control, or workload reduction remains to be seen. The present subjects relied less on the computer checklist as they gained greater experience with the entire system.

Realizing that the particular system architecture and input/output system design that is used can influence how effectively users interact with one another remotely, it will be vitally necessary to continue to carry out rapid prototyping studies using flight hardware and operational procedures well before the actual flight. Such studies will help identify many problem areas and means for solving them.

Distributed Task Coordination

When a group of people work together in tight collaboration on a pre-defined task, such as repairing a complicated device, performing a laboratory experiment, or preparing an aircraft for flight, the task can usually be described as a partial ordered list of subtasks, where each subtask is an indivisible unit of work typically performed by a single individual. The list is typically represented as a written set of instructions, as in a checklist or repair manual, or as a graphic chart. When the group of people are working in close physical proximity, synchronization is typically simplified by the use of verbal communication, or a task supervisor overseeing the progress. In the former case, the task list can be shared, or replicated for each member. In the latter, typically only the supervisor has the task list and gives instructions or orders to each subordinate member. However, when the group is geographically dispersed, such tight communication or supervision is not as simple. Radio links can be used for verbal and video communication, and the task list is represented on paper and available to each member of the group. Voice and video can be used in the supervisor model, as well, with the supervisor parcelling out instructions in the correct order.

Though audio networks are commonplace (the telephone system), personal video networks are not yet commonly available. Digital computer networks, however, have become more and more available to the science community, and predictions are that the trend will continue for many years. Hence, we are investigating how these networks, and the workstations people use to interface to them, can be used to support collaborative task sequencing.

The remote coaching facility uses a simple sequencer in which the subtasks form a total semi-rigid ordering. Such task sequences can be called a "check list" because each subtask must be completed ("checked off") before then next one begins. There is no possibility for parallelism, although advanced versions may offer this possibility given adequately structured synchronizations.

Complete seriality is not inherent to task sequencing; procedures often provide for simultaneous activities. A computer-support task synchronizer that supports simultaneous activities can also support completely serial activities by simply providing it with a serial specification. However, we do not yet understand all the issues related to task synchronization supporting simultaneous activities, or if such has practical application for dispersed collaborators. Hence, we chose to study only the completely serial case at first.

We chose to approach this project incrementally. Because of the experiences gained in the remote coaching study, we chose to mimic the software developed therein as our starting point. However, the initial prototype software was developed solely for Apple Macintoshes and is written using the HyperCard application. Our computing environment relies on open systems, and our software platform includes UNIX, the X Window System, and the Motif toolkit. We did not restrict ourselves to any particular hardware platform.

We succeeded in this goal and have a configurable distributed checklist application that is transportable across many workstation platforms. We have demonstrated this code by creating working displays on Sun Microsystems workstations, a Stardent Titan-1000, an Apple Macintosh II, and a NCD X-station, all at the same time.

The design goal of phase zero was to allow the specification of the checklist task as a simple text file, that can be created using any standard text editor. We designed and implemented a straightforward textual language to describe the checklist. The application itself is composed of two major phases: input processing and interpretation.

The distributed checklist (DCL) application is constructed as a single process that simultaneously manages several displays, one per participant. This capability takes advantage of the ability of the X Window System to support remote displays. In fact, the DCL application code need not run on the same display workstation as any of the displays.

Critical to usefulness of a distributed checklist is keeping all participants aware of the state of the procedure. Hence, much of the activity of the application concerns assuring that all displays reflect the same state.

Conclusions

Collaboration technology has a potentially vital role to play in future space science and missions. Integration of this technology into a useful system is the critical issue to be addressed. We explored a specific application of this technology to remote coaching, and developed a prototype tool to support such remote coaching. The results will help define the requirements and specifications of future systems.

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